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9 FINAL TECHNICAL REPORT

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AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

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CORNELL UNIVERSITY
DEPARTMENT OF GEOLOGICAL SCIENCES
ITHACA, NEW YORK 14853

Title of Proposal:	6 Global Investigation of Seismic Wave Propagation on a Regional Scale.
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Co-Principal Investigator:	Bryan L. Isacks
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The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the Defense Advanced Research Projects Agency or the U.S. Government.

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TECHNICAL REPORT SUMMARY

Research Objectives:

The goals of this study are (1) to provide a regional seismological "catalog" of patterns of high-frequency seismic wave propagation and velocities at regional distances in the Middle East and Eurasia, (2) to understand the causes for such observed patterns, and (3) to relate the observed lateral variations in wave propagation to the known surface and subsurface geological and geophysical data. These goals are of direct relevance to the objectives of DARPA, which include the development of regionalized wave propagation models for various seismic phases from Eurasian sources. It is essential for any successful program of detection and identification of nuclear explosions to document and understand the patterns of wave propagation at regional distances in the regions of interest. The results of our research program have certainly contributed significantly toward these objectives, as specified by DARPA.

Accomplishments:

The Middle East study is focused on the Turkish and Iranian plateaus and the surrounding regions. Sn amplitude variations are very striking in these areas. Efficient Sn propagation is observed across a major part of the Turkish and Iranian plateaus. However, Sn is strongly attenuated in the northernmost part of the plateaus south of the Black and Caspian Seas, and in the area between these two seas. These regions are characterized, in general, by active tectonism, including volcanism, faulting, and folding. However, this active tectonism is not restricted to the areas of high Sn attenuation, but appears to extend, though with somewhat less apparent activity, beneath a major part of the Turkish and Iranian

plateaus.

Patterns of lateral variations in the propagation of Lg are not as consistent as those for Sn. Lg propagates efficiently across Turkey, Iran and adjacent regions, but the Lg waves that cross the Turkish and Iranian plateaus are, in general, weak and have relatively long predominant periods of about 2-5 seconds. The Lg phase is not observed when the path of propagation crosses the southern Caspian and the Black Seas, consistent with the available evidence of oceanic-type crustal structure beneath these seas. The observed variations in the properties of the Lg phase in the Middle East suggest that this phase may not be very useful with regard to the objectives of DARPA in this region.

The velocity of Pn beneath most of the Turkish and Iranian plateaus, including the regions of high Sn attenuation, ranges between 8.0 and 8.2 km/sec. Thus, in contrast to many other areas of high Sn attenuation, the Pn velocity is not anomalously low. Velocities for Sn and Lg throughout the Middle East are about 4.5 and 3.4 km/sec, respectively.

Our study of wave propagation at regional distances beneath south-central Asia is near completion. The observations can be interpreted best, though not uniquely, to indicate the underthrusting of the Greater Indian continental lithosphere beneath most of the Tibetan plateau. This shallow-angle underthrusting results in a double thickness of the continental crust beneath the present-day Tibetan plateau. This model is inferred from seismological observations based on visual examination of hundreds of short-period WWSSN seismograms recorded at stations located to the south and west of the Himalayan arc and produced by earthquakes located at regional distances. The most striking observation is that high-frequency Sn waves propagate efficiently in the uppermost mantle beneath most of the

Tibetan plateau, except the northern part. Velocities of $\underline{Pn}$ and $\underline{Sn}$ waves that traverse the uppermost mantle beneath the Tibetan plateau are about 8.4 and 4.7 km/sec, respectively. These uppermost mantle velocities are very similar to those beneath the Himalayan mountains. The efficient propagation and the velocities of $\underline{Pn}$ and $\underline{Sn}$ waves beneath Tibet are also similar to those commonly observed beneath shield and stable continental regions. These results are consistent with the above model and do not favor the class of alternative models in which Tibet is formed by crustal shortening and thickening of hot material in response to the convergence of India and Asia.

Furthermore $\underline{Sn}$ efficiently propagates across the stable block of the Tarim basin and along the Himalayan and Tien Shan mountains. There is a zone of inefficient $\underline{Sn}$ propagation in the uppermost mantle beneath the northern part of Tibet, the Chang Thang terrane. The occurrence of subrecent volcanism (basaltic?) in the Chang Thang suggests a genetic relationship between these volcanics and the mapped zone of inefficient $\underline{Sn}$ propagation.

$\underline{Lg}$ propagates efficiently along paths that are approximately parallel to the structural trends of the mountain belts in the region, including the Himalayas and Tien Shan. However, $\underline{Lg}$ is not observed when the propagation paths are transverse to the mountain belts. This suggests that scattering of $\underline{Lg}$ due to abrupt changes in the crustal structure near the front of the mountain belts is probably the main cause for the observed inefficient propagation of $\underline{Lg}$ beneath the Tibetan plateau.

Finally, we have recently initiated an investigation of the effects of the source depth on the excitation and propagation of the different seismic phases at regional distances. Specifically we have investigated the depth

of the main shock and aftershocks of the Khurgu sequence (March 21, 1977) located in the southernmost part of the Zagros mountain belt in Iran using a computer algorithm to generate synthetic long-period seismograms. Preliminary results show that the depth of the main shock is about 16 km, clearly within the inferred Precambrian basement in the region.

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DETAILED DISCUSSION OF ACCOMPLISHED AND CURRENT RESEARCH

The original plan of our study was to investigate in detail the variations in the properties of many seismic phases at regional distances, including Pn, Pg, Sn, Lg, Rg, and PL amongst others. However, after some preliminary work we have concentrated our investigation on the seismic phases Pn, Sn, and Lg since these phases exhibit striking variations in their propagation characteristics and velocities from region to region. The results of our studies are based on the massive analog data produced by the numerous WWSSN stations in the region. To document patterns of wave propagation we have examined all possible source-station paths available, and we present the detailed results on wave propagation in a form that can be easily understood. The results probably represent the most detailed compilation available in the literature.

The Middle East Study:

During the first phase of our research program supported by DARPA, our efforts were mainly devoted to a detailed study of seismic-wave propagation in the Middle East. Knowledge of the pattern of wave propagation across this region, especially short-period waves, is essential for any successful program for the identification and detection of nuclear explosions originating in Eurasian regions. Moreover, the presence of the Iranian and Turkish plateaus in the Middle East region provides an excellent opportunity to study the effect of these high elevated regions, which are characterized by active surface faulting and active and recent volcanism, on the propagation of high-frequency seismic waves.

Thousands of short-period seismograms produced at WWSSN stations in the region were examined for the presence or absence of the short-period

phases $\underline{Pn}$, $\underline{Pg}$, $\underline{Sn}$, and $\underline{Lg}$; in particular, the relative amplitudes and the arrival times of these phases were obtained for any given station. Events that occurred between 1962 and 1978 were used. Only events located at distances between 3° and 25° were considered. The locations and the origin times of the events and the epicentral distances were taken from the Bulletin of the International Seismological Centre. However, the arrival times of the different seismic phases were read by us directly from the records. Phases that have too emergent beginnings were excluded from the travel-time analyses. Data produced by the following WWSSN stations were used in this study: QUE (Quetta, Pakistan), TAB (Tabriz, Iran) SHI (Shiraz, Iran), IST (Istanbul, Turkey), and EIL (Eilat, Israel).

The most striking observation of this study is the inefficient propagation of $\underline{Sn}$ across the northern part of the Iranian plateau and across the eastern and northern parts of the Turkish plateau. A likely explanation for this phenomenon is that a zone of high-attenuation, low-Q material exists in the uppermost mantle beneath this region. Though $\underline{Sn}$ propagates efficiently across the rest of the Turkish and Iranian plateaus, the amplitudes of the waves are, in general, smaller than those for $\underline{P}$ waves. This is in contrast to the large $\underline{Sn}$ amplitudes relative to $\underline{P}$-wave amplitudes across other regions in the Middle East, such as northern Arabia and Pakistan.

Lateral variations in the propagation of the crustal phase $\underline{Lg}$ are less consistent than those observed for $\underline{Sn}$. Inefficient $\underline{Lg}$ propagation is primarily observed when the path crosses an oceanic region, such as the Red Sea and the Arabian Sea. An interesting observation is that $\underline{Lg}$ does not propagate across the deep parts of the Caspian and the Black seas, implying an oceanic-type structure beneath these parts. Also, $\underline{Lg}$ seems not to be

excited by the sub-crustal events located beneath the Hindu Kush region. Lg waves that propagate across the Iranian and Turkish plateaus are, in general, weak and have longer periods (2-5 seconds) as recorded on the short-period components. This is in marked contrast to the very large (larger than Pn and Sn) amplitudes and higher-frequency Lg observed along nearby regions and other continental regions such as the eastern U.S. Apparent velocities of 8.2, 4.5, and 3.4 km/sec were obtained for Pn, Sn, and Lg phases, respectively. The Pn velocities seem to be similar whether the propagation paths cross efficient or inefficient Sn regions. The average Pn velocity we determined in Iran and Turkey (8.2 km/sec) appears to be higher than those determined by Chen et al. (1980) for Turkey (7.7 km/sec) and Iran (8.0 km/sec). However, velocities obtained in these two studies should be considered preliminary and represent an average determination of many different physiographic and tectonic features (see Figures 1-10).

Our study of the Middle East is completed. The paper that reports the results of this study is submitted to the Journal of Geophysical Research, and is accepted for publication (Kadinsky-Cade et al., 1981). Also, we presented the results of our research at the Fall meeting (1979) of the American Geophysical Union and at the International Union of Geodesy and Geophysics meeting (1979) in Canberra, Australia.

The South-Central Asia Study:

Our investigation of the velocities and wave propagation of the Pn, Sn, and Lg seismic phases across India, the Himalayas, the Tibetan plateau, the Tarim basin, Tien Shan, Hindu Kush-Pamir, and the surrounding regions is near completion. The results of this study will be presented during the coming A.G.U. meeting in May, 1981 in Baltimore, and during the coming

IASPEI meeting in July, 1981 in Canada (Barazangi and Ni, 1981).

The results of this study are relatively more simple and more consistent than those obtained in the Middle East study, and the conclusions that can be drawn from these results are very important with regard to the geological evolution of the region in general and, in particular, the Tibetan plateau. The results suggest that the Greater Indian continental lithosphere is being underthrust beneath most of the Tibetan plateau. This underthrusting may explain the relatively uniform high elevation of the plateau as well as the simple arc-shape geometry of the Himalayan arc. Moreover, this shallow-angle underthrusting results in a double thickness of the continental crust beneath the Himalayan mountains and the Tibetan plateau, in accord with the available geophysical data.

The above results and conclusions are based on the visual examination of hundreds of short-period seismograms recorded at the numerous WWSSN stations in the region and produced by shallow events located at regional distances that occurred between 1962 and 1978. Data produced by the following stations have been used so far: KBL-Kabul, Afghanistan, NDI-New Delhi, SHL-Shillong, and POO-Poona, India. The records are examined for the presence or absence of the different seismic phases, especially Pn, Sn, and Lg. The arrival times and the relative amplitudes of these phases are documented by us directly from the analog records. To minimize the error in the calculation of velocities based on the arrival time data we have selected events that are relatively well-located by the International Seismological Centre (ISC) with focal depths that range only between about 20 to 40 km.

The most important observations of this study are (see Figures 11-15):

1. Sn propagates very efficiently beneath most of the Tibetan

plateau, beneath the Tarim basin stable block, along the Himalayan-Tien Shan-Hindu Kush-Pamir-Karakoram mountain belts, and beneath the Indian shield. The efficient Sn propagation beneath most of the Tibetan plateau is of particular importance since it suggests that the uppermost mantle material beneath most of Tibet is not anomalous (e.g., not anomalously hot and/or partially melted). This efficient Sn propagation is similar to that usually observed across shield and stable continental regions, such as the eastern U.S., the Canadian shield, and the Indian shield. The Pn and Sn velocities determined in this study beneath Tibet are 8.42 and 4.73 km/sec, respectively. These relatively high uppermost mantle velocities support the above inference that there is no anomalous uppermost mantle material beneath most of Tibet. Another interesting observation is that Sn efficiently propagates across different mountain belts. This suggests that variations in the crustal structures do not affect, in general, the propagation of Sn.

2. Sn is not observed for propagation paths that cross the northern part of the Tibetan plateau, the Chang Thang terrane. The inefficient Sn propagation suggests that a zone of high attenuation exists in the uppermost mantle beneath the Chang Thang. This zone of high attenuation appears to be confined in the north to the physiographic boundary of the Tibetan plateau and appears not to extend beneath the Tsaidam basin block. Moreover, the zone of high attenuation as mapped in this study appears to be spatially related to the reported widespread subrecent volcanics (basaltic?) in the Chang Thang terrane; a genetic relationship must exist between the two phenomena.

3. A consistent Lg propagation pattern is observed in this region of south-central Asia. Lg is not observed when the propagation paths are

transverse to the mountain belts, even for relatively very short epicentral distances. _Lg_, however, efficiently propagates when the paths are approximately parallel to the structural trends of the mountains. The above observations suggest that scattering of _Lg_ due to lateral variations in the crustal structure near the front of mountain belts is probably the main cause for the observed inefficient _Lg_ propagation beneath the Tibetan plateau.

Depth of Source Study:

The accurate determination of earthquake depths in southern Iran is essential to wave propagation studies and to tectonic models in that region. The excitation of _Sn_ and _Lg_ phases has been shown to depend on the source depth, for example, in Papua-New Guinea (Barazangi, Oliver, and Isacks, 1977). Accurate earthquake depths in southern Iran should also provide some information on the nature of the transition between the region of continental collision in the Zagros mountains and the inferred oceanic subduction zone in the adjacent Makran region to the southeast of the Zagros. Accurate earthquake depths are difficult to obtain from teleseismic _pP_ readings due to the shallow depths of most of the events in this area (see Figure 16). Local networks do not provide sufficient coverage of this zone, where large earthquakes have occurred repeatedly.

An effective method for determining earthquake depths has been used by Chinn and Isacks (1979) in South America and in the New Hebrides. It is based on an algorithm developed by Langston and Helmberger (1975) which compares actual seismograms with calculated body wave synthetic seismograms from dislocation sources which are embedded in a layered elastic medium. It uses a ray theory approach based on the interpretation of ray arrival times and amplitudes (see Figure 17).

The region under study is shown in Figure 16. The seismicity trends in this area show some interesting features. A relatively wide belt of shallow seismicity occurs beneath the Zagros mountains in the west and halts abruptly north of Oman along a northeast-trending structure, i.e., the inferred Oman Line. To the east of this zone there is much less activity. Greater earthquake depths have been reported in the latter area.

A specific earthquake was selected from this region for initial testing of our depth program: The main shock of the Khurgu sequence (March 21, 1977; mb = 6.2; 27.59^o N, 56.37^o E). Before actually applying the depth program to this event it was necessay to obtain an accurate focal mechanism and to assume a reasonable crustal velocity model at the source. The focal mechanism data are shown in Figure 18, based on WWSSN long-period recordings, and include P-wave first motions and S-wave polarization angles. As all P arrivals are compressional, the mechanism is assumed to be one of simple thrusting. The amount of strike-slip component which can be included in the solution is very small. The strike of the fault planes can vary between 73° and 108° (dip to the north) or between 150° and 130° (dip to the northeast). The distribution of aftershocks agrees with the more east-west trending nodal planes; thus a pure thrust solution in the first category was picked, with parameters: strike 90°, dip 30° N, 60° S (see Figure 18). The crustal velocity model was not well-constrained, due to the lack of seismic refraction and deep reflection data in this area. An aeromagnetic survey by Morris (1977) estimates a depth to basement of 8-9 km at Khurgu (Jackson and Fitch, 1981). The model used in our analysis includes 5 km of sediments (Vp = 5.00 km/sec, Vs = 2.89 km/sec) and crustal values of Vp = 6.30 km/sec, Vs = 3.64 km/sec down to the depth of the earthquake.

Using the above focal mechanism and simple crustal structure, matching of observed and synthetic seismograms is presented in Figure 18 which shows observed and best-matching synthetic P waveforms for 12 stations as well as relative amplitudes and arrival times of the major phases contributing to these waveforms. An enlarged version of one of the relative amplitude-arrival time plots is shown in Figure 17, for the station WIN. Figure 17 also shows a model which includes all the phases considered by the ray program. Only the phases which are large enough to be plotted (and hence large enough to affect the waveform) are shown. A number of tests were done to determine the effects on the waveform of varying the following parameters: V_p, V_s, sediment thickness, source time-function, focal mechanism and, most importantly, depth.

The average depth determined in this study for the main shock of the Khurgu sequence is 16 km. This depth is well within the inferred Precambrian basement in this region. We plan to continue working on determining the depths of other events in the region, and to investigate the effects of varying the depth of the sources on the regional wave propagation.

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Morris, P., 1977, Basement structure as suggested by aeromagnetic surveys in S.W. Iran, *Oil Service Company of Iran*, internal report.
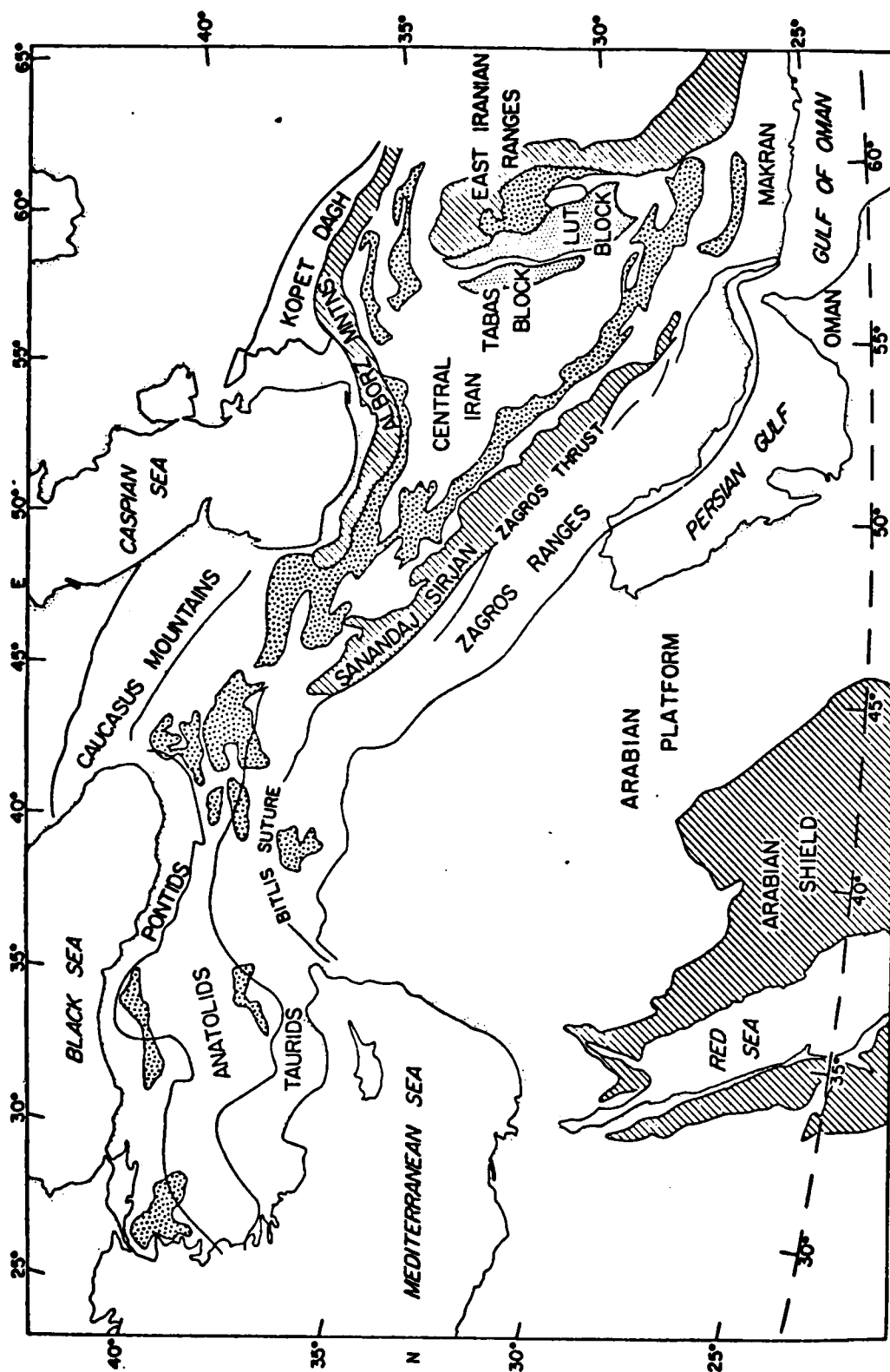
Figure 1. Map showing location of major physiographic and tectonic provinces discussed in the text. Hatchured areas correspond to location of individual ranges. The Pontids, Anatolids, and Taurids in Turkey are separated by boundary lines. Dotted areas are Cenozoic volcanics in Iran and Turkey. The Tabas and Lut blocks in Iran are shown by a different pattern. The Afro-Arabian volcanics are not shown.
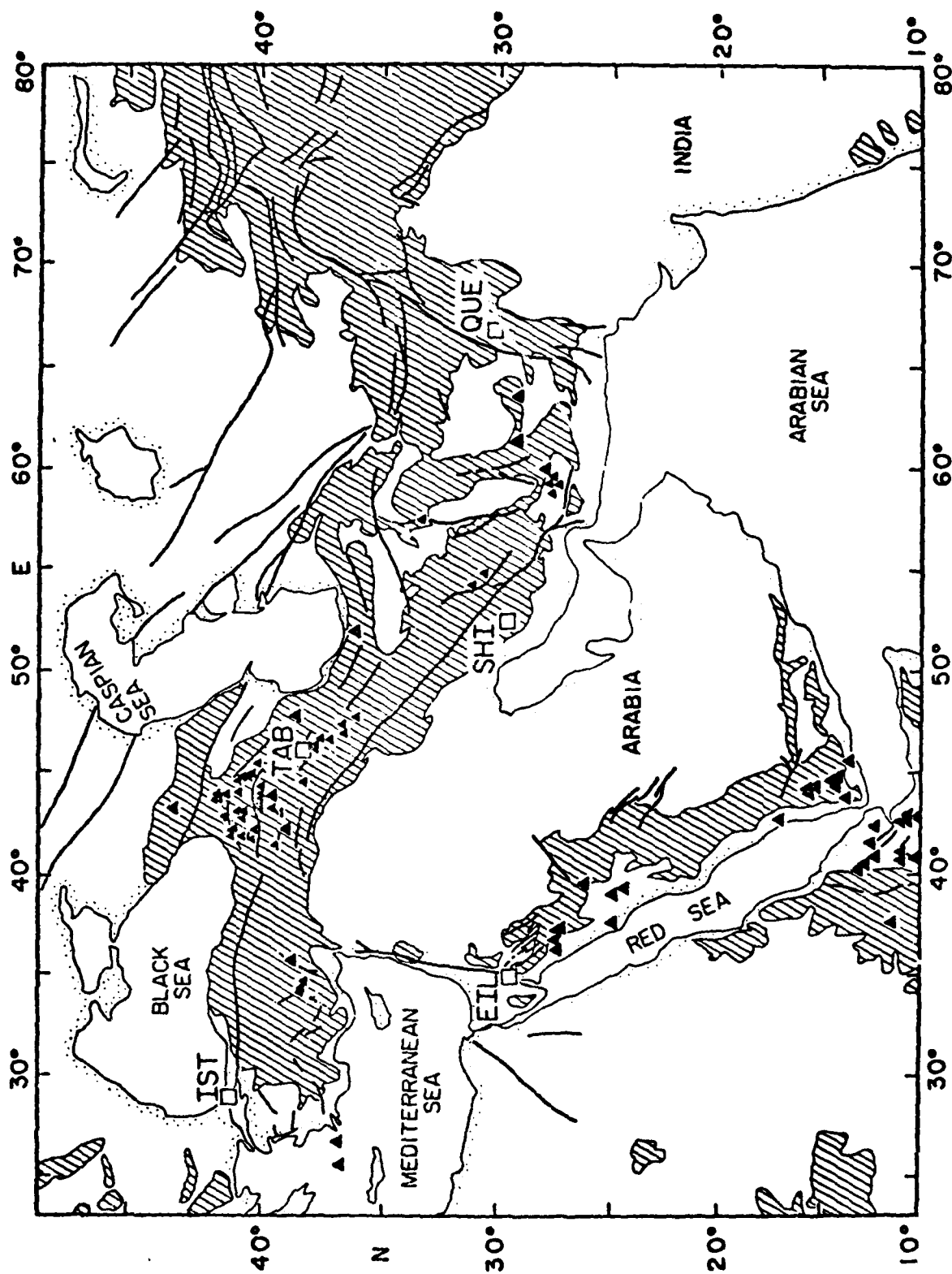
Figure 2. Generalized map of the Middle East (Mercator projection), showing WWSSN seismic stations used, elevations over 1.0 km (shaded areas), and major faults and volcanoes (historically active and Quaternary). Note the Iranian-Turkish plateau located to the north of the Zagros-Bitlis suture zone.
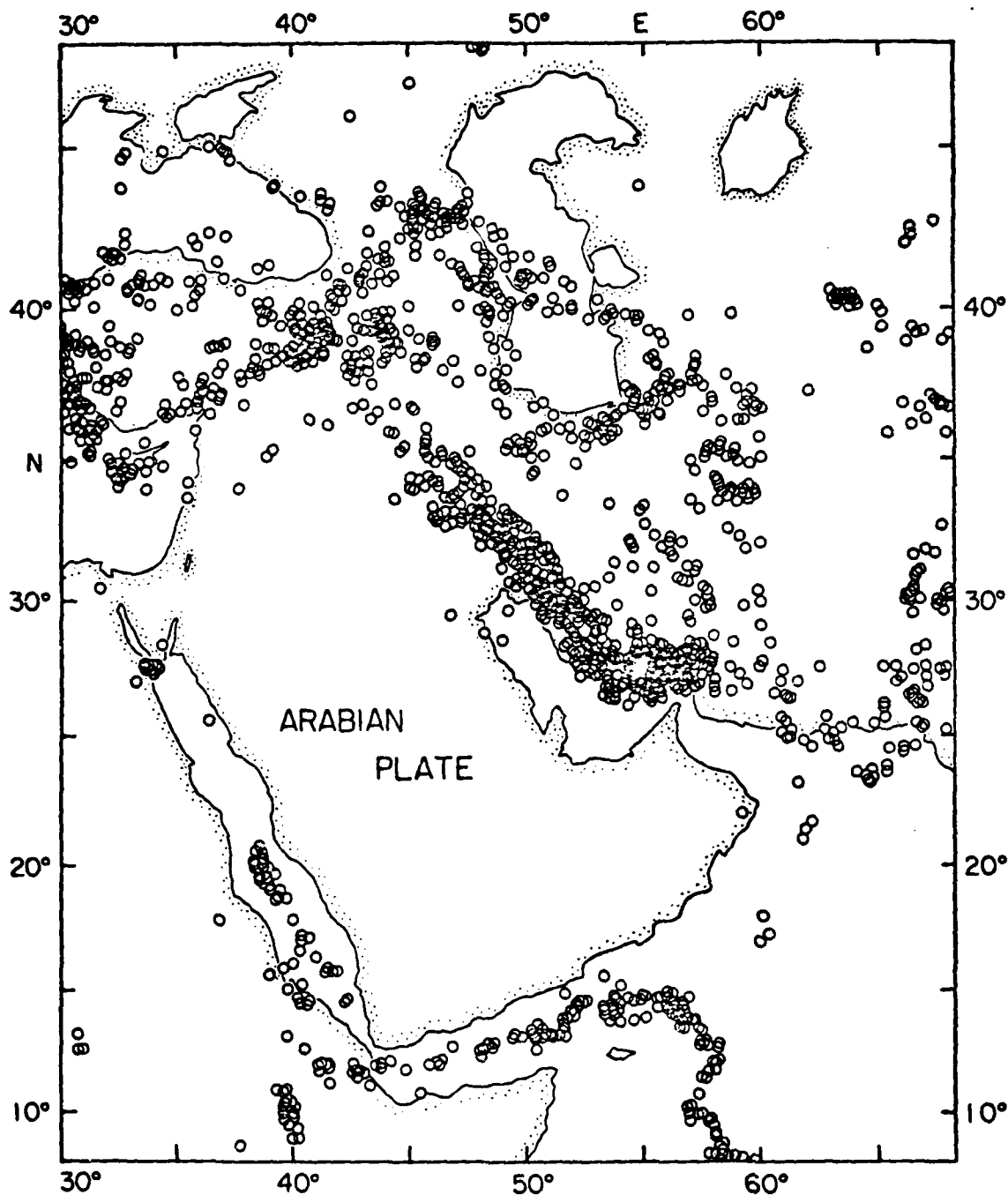
Figure 3. Seismicity map of the Middle East, from USGS Preliminary Determination of Epicenters, 1962-1977. Records produced by these abundant events at the different WWSSN stations in the Middle East are used in this study.
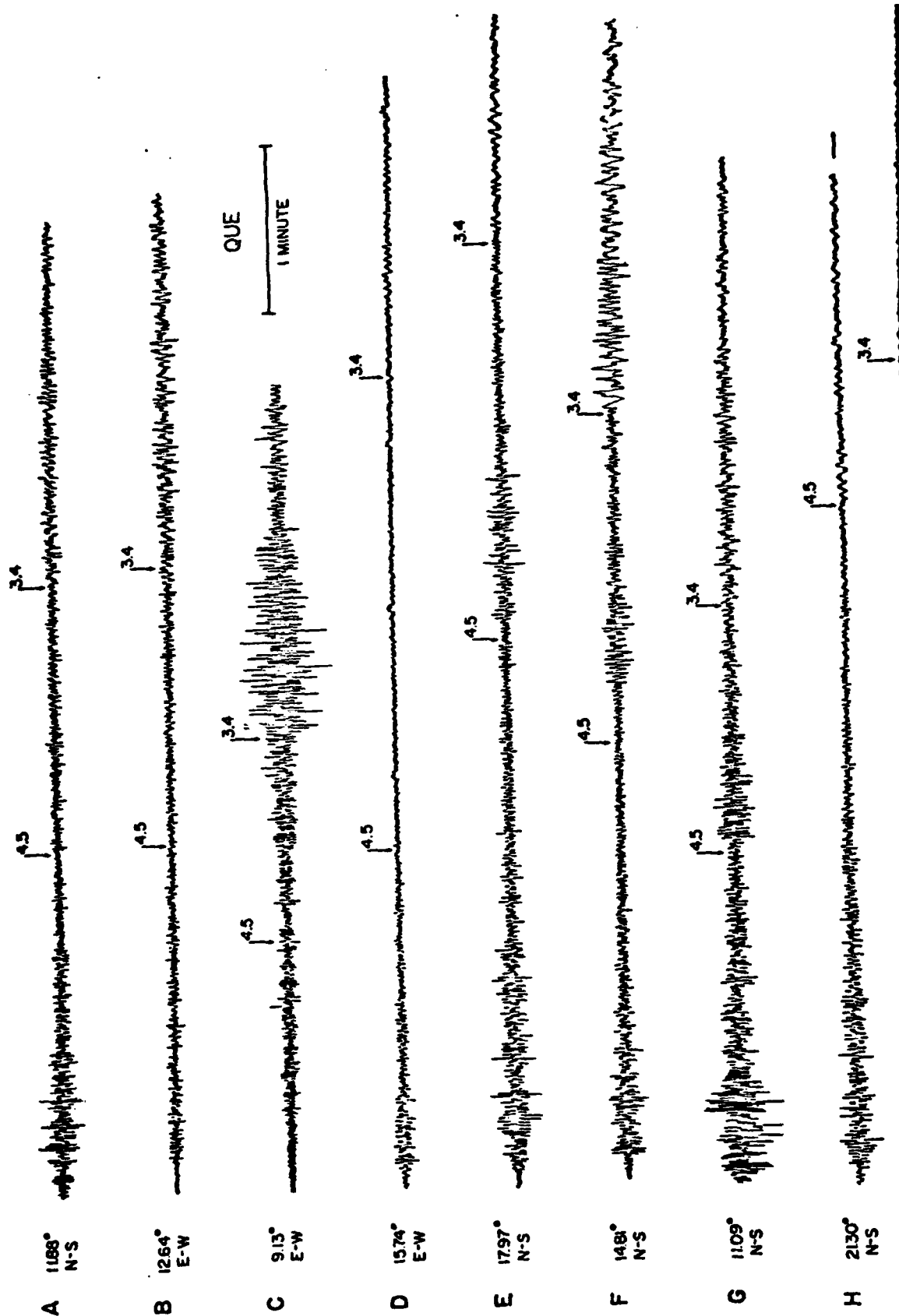
Figure 4. Representative short-period seismograms recorded at QUE and produced by shallow events shown in Figures 6 and 7 (if the events are subcrustal then the depths are shown). The records are aligned according to P waves. Arrival times corresponding to velocities of 4.5 and 3.4 km/sec, average velocities of Sn and Lg, respectively, in the area of study are indicated by arrows. Also shown are the epicentral distances of the events and the short-period component represented.
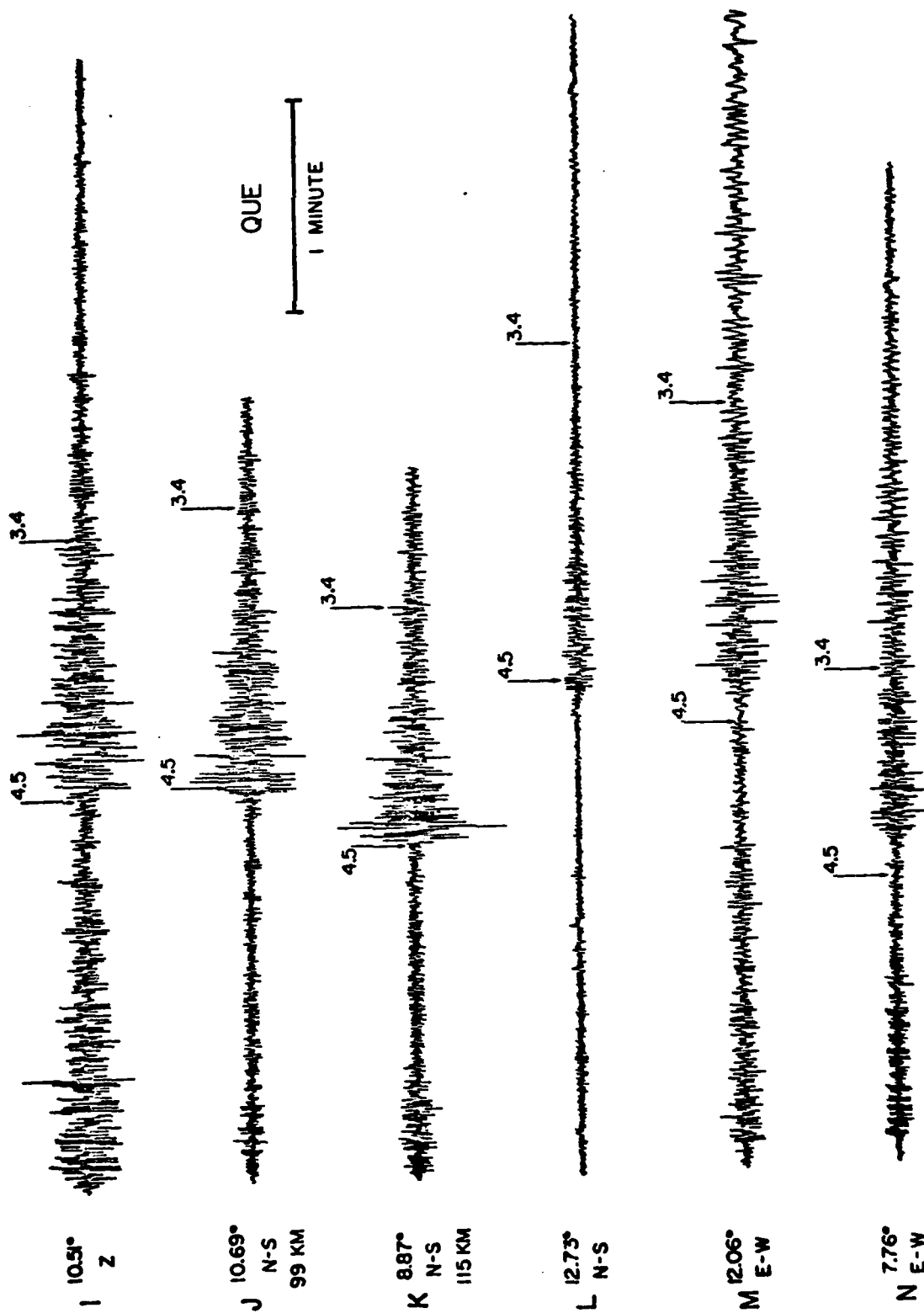
Figure 5. Representative seismograms recorded at QUE, continued from Figure 4.
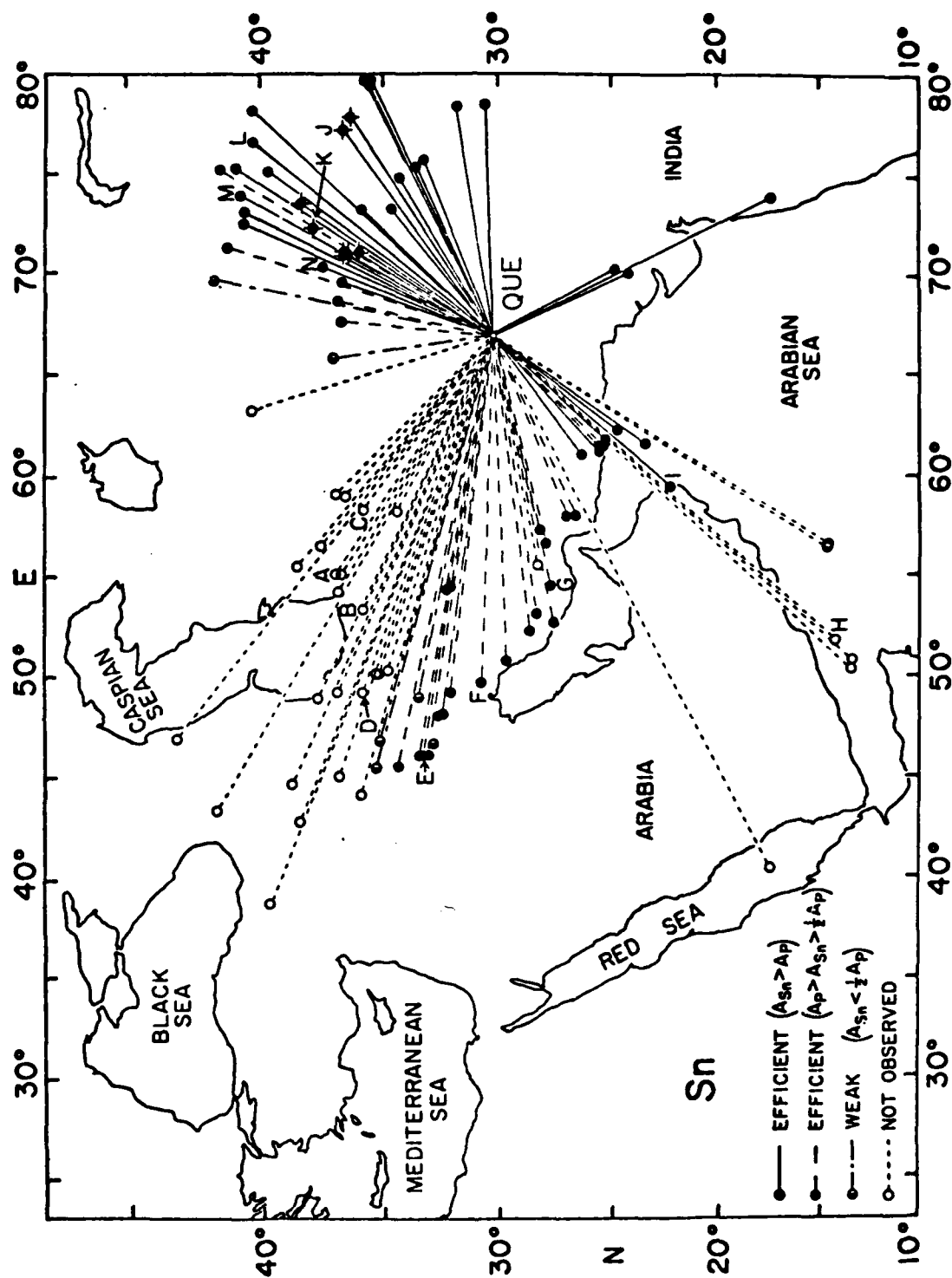
Figure 6. Pattern of Sn propagation recorded at QUE. Sn amplitudes are classified relative to those of Pn, as described in the figure. Crosses represent events of intermediate depths. Identifying letters correspond to seismograms shown in Figures 4 and 5.
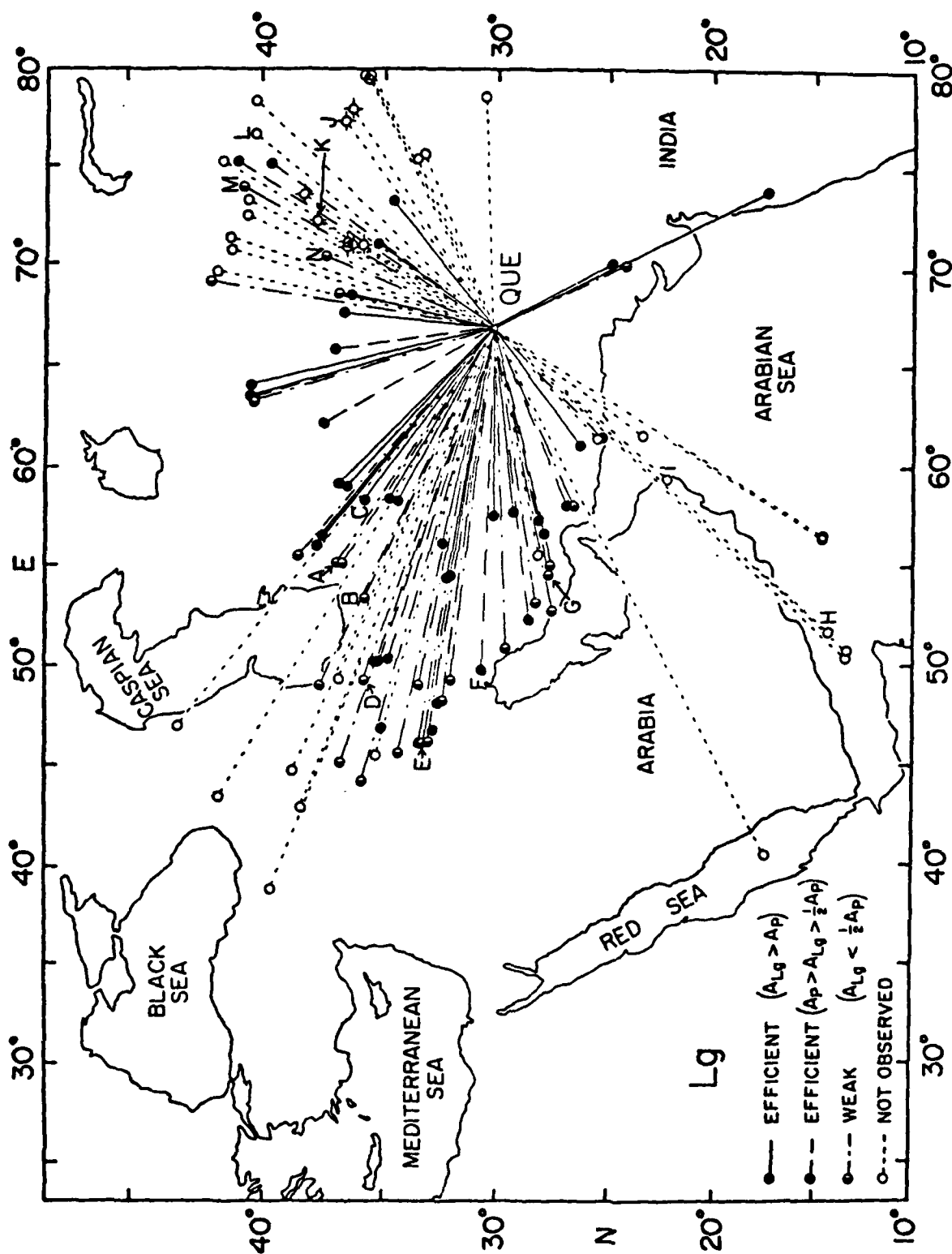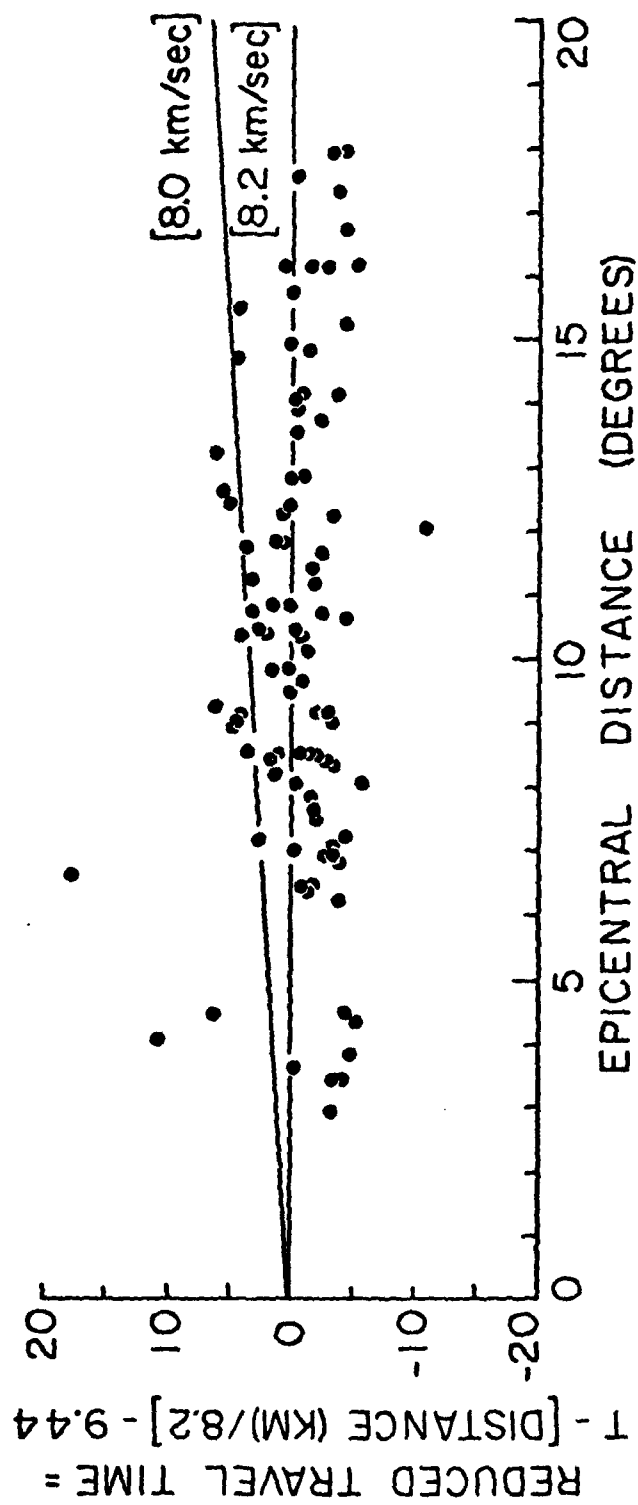
Figure 7. Pattern of _Lg_ propagation recorded at QUE. _Lg_ amplitudes are classified relative to those of _Pg_, as described in the figure. Crosses represent events of intermediate depths. Identifying letters correspond to seismograms shown in Figures 4 and 5.

Figure 8. *Pn* travel-time plot for propagation paths that are mostly contained in the plateau regions, including data from IST-east, TAB-southeast, SHI-northeast, QUE-southwest, and QUE-northwest. The calculated velocity for these data points is 8.2 km/sec (8.0 km/sec is shown for comparison).
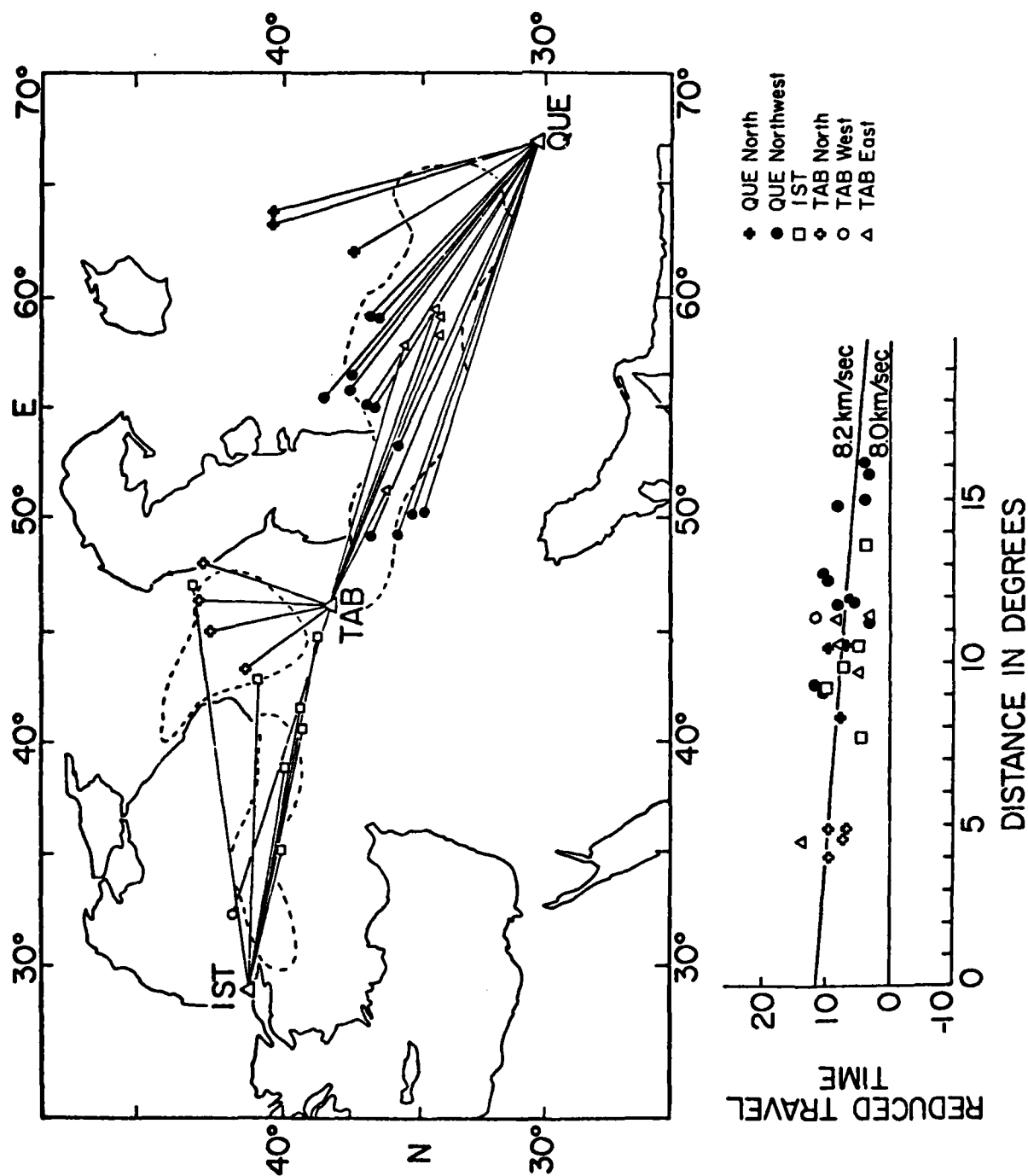
Figure 9. Travel-time plot for <u>Pn</u> propagation paths that are mostly contained in <u>Sn</u> attenuation zones (as defined by dashed lines on the map). Paths are shown on the map. The velocity obtained is 8.2 km/sec.
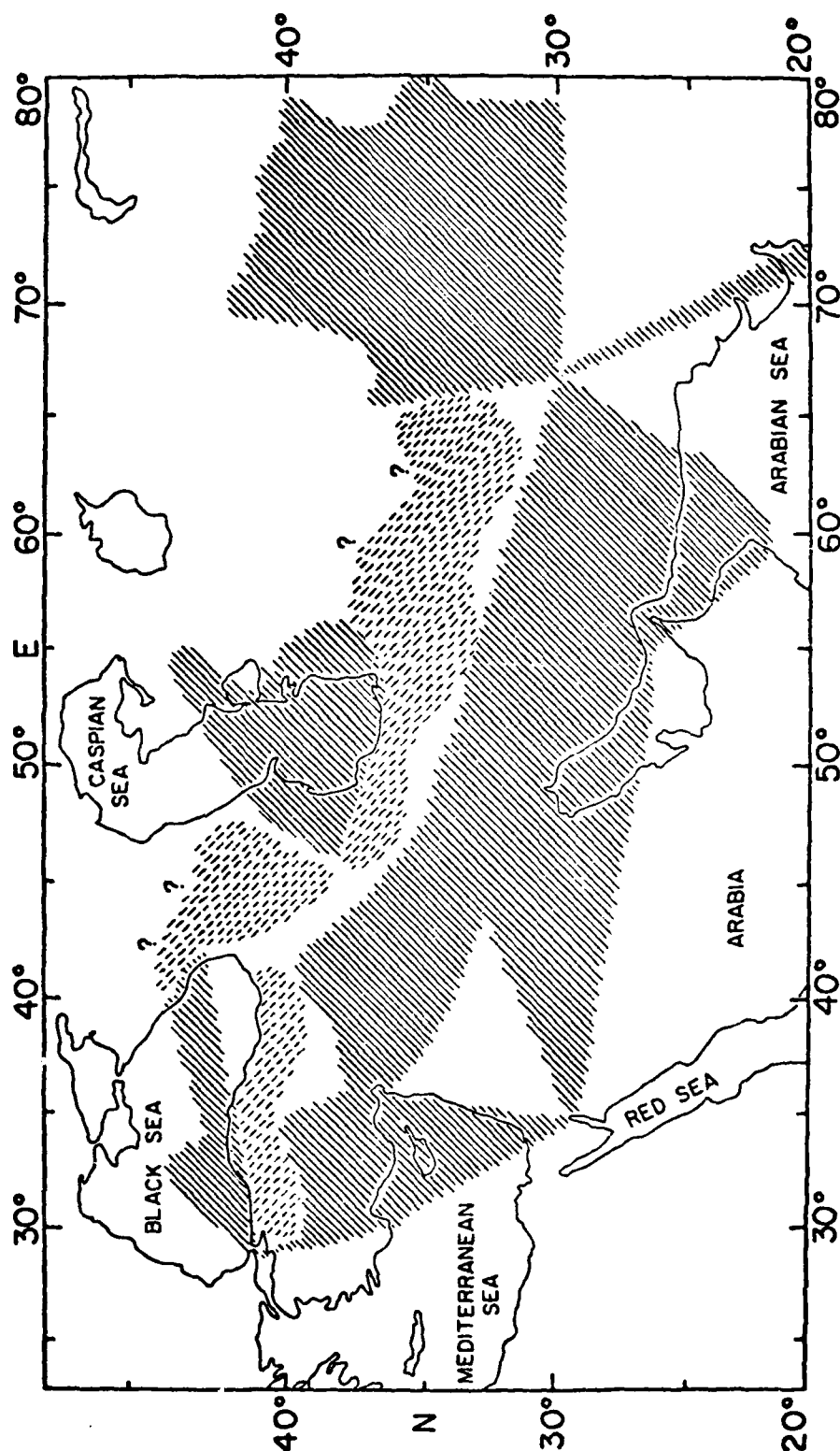
Figure 10. Map of the Middle East showing zones of efficient (solid lines) and inefficient (dashed lines) Sn propagation. Question marks indicate that the northern boundaries of the zones are, in general, not well-known. The inefficient Sn propagation suggests that zones of high-attenuation (low Q) exist in the uppermost mantle beneath the northern part of the Iranian plateau and the northern and eastern parts of the Turkish plateau.
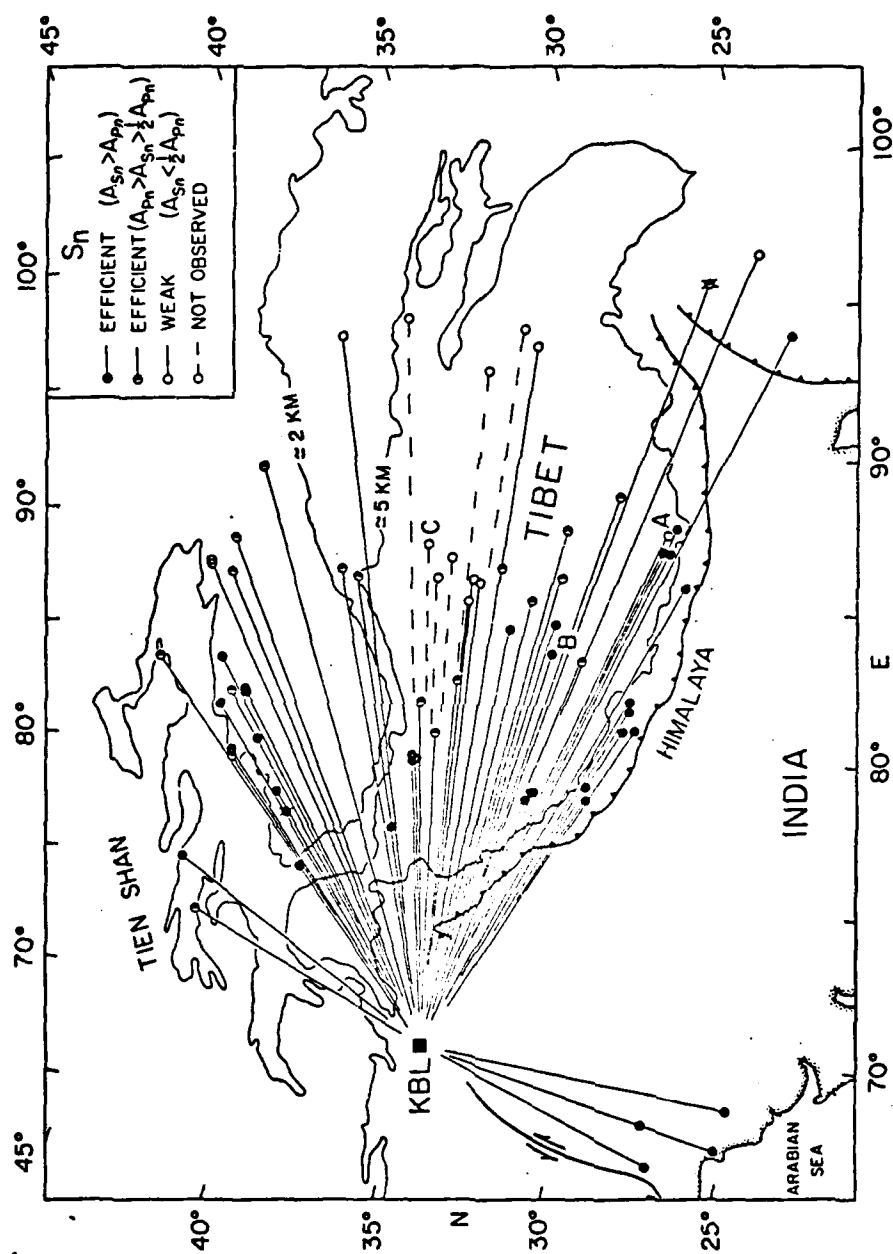
Figure 11: Pattern of Sn propagation recorded at KBL station. Sn amplitudes are classified relative to those of Pn, as shown on the figure. Identifying letters correspond to seismograms shown in Figure 13.
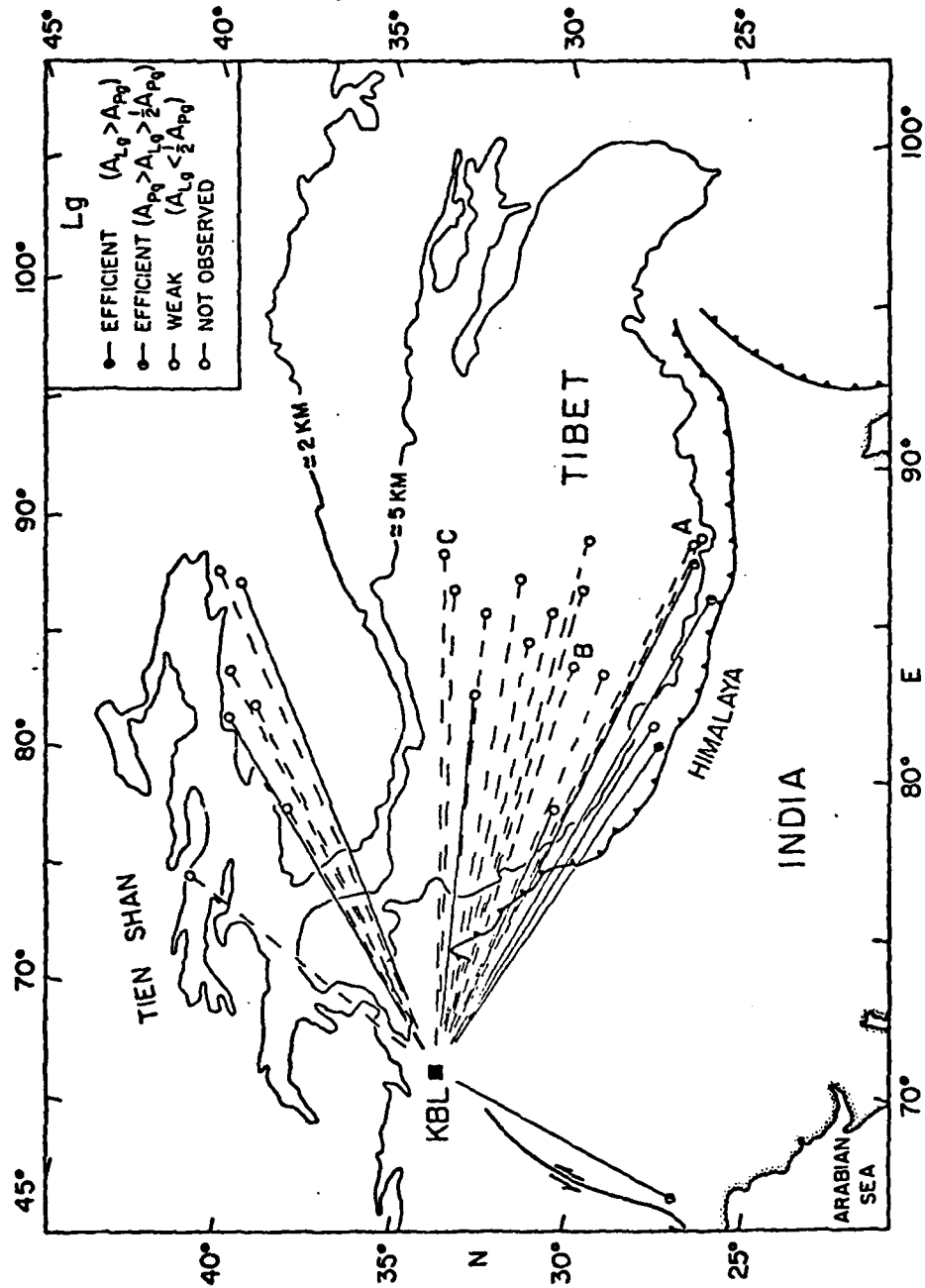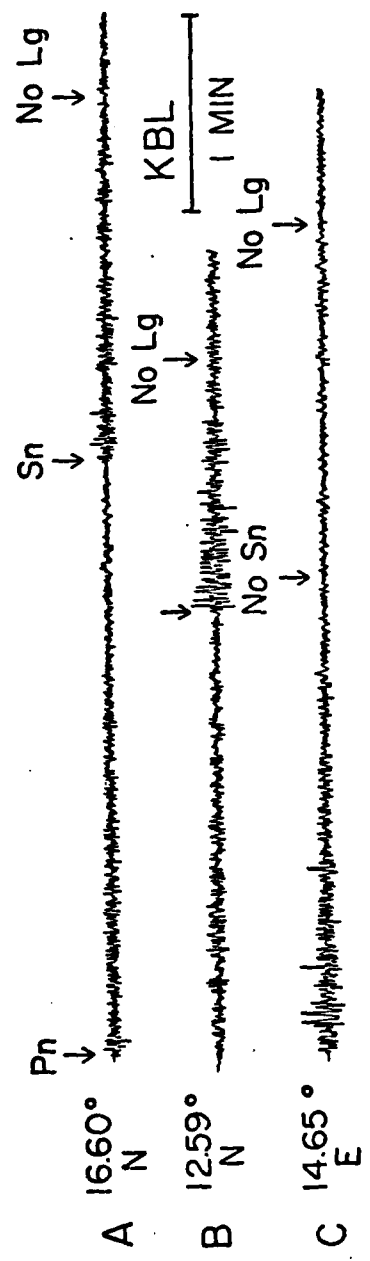
Figure 12: Pattern of _Lg_ propagation recorded at KBL station. _Lg_ amplitudes are classified relative to those of _Pg_, as shown on the figure. Identifying letters correspond to seismograms shown in Figure 13.

Figure 13: Representative short-period seismograms recorded at KBL and produced by shallow events shown in Figures 11 and 12. The epicentral distances of the events and the short-period component represented are also shown.
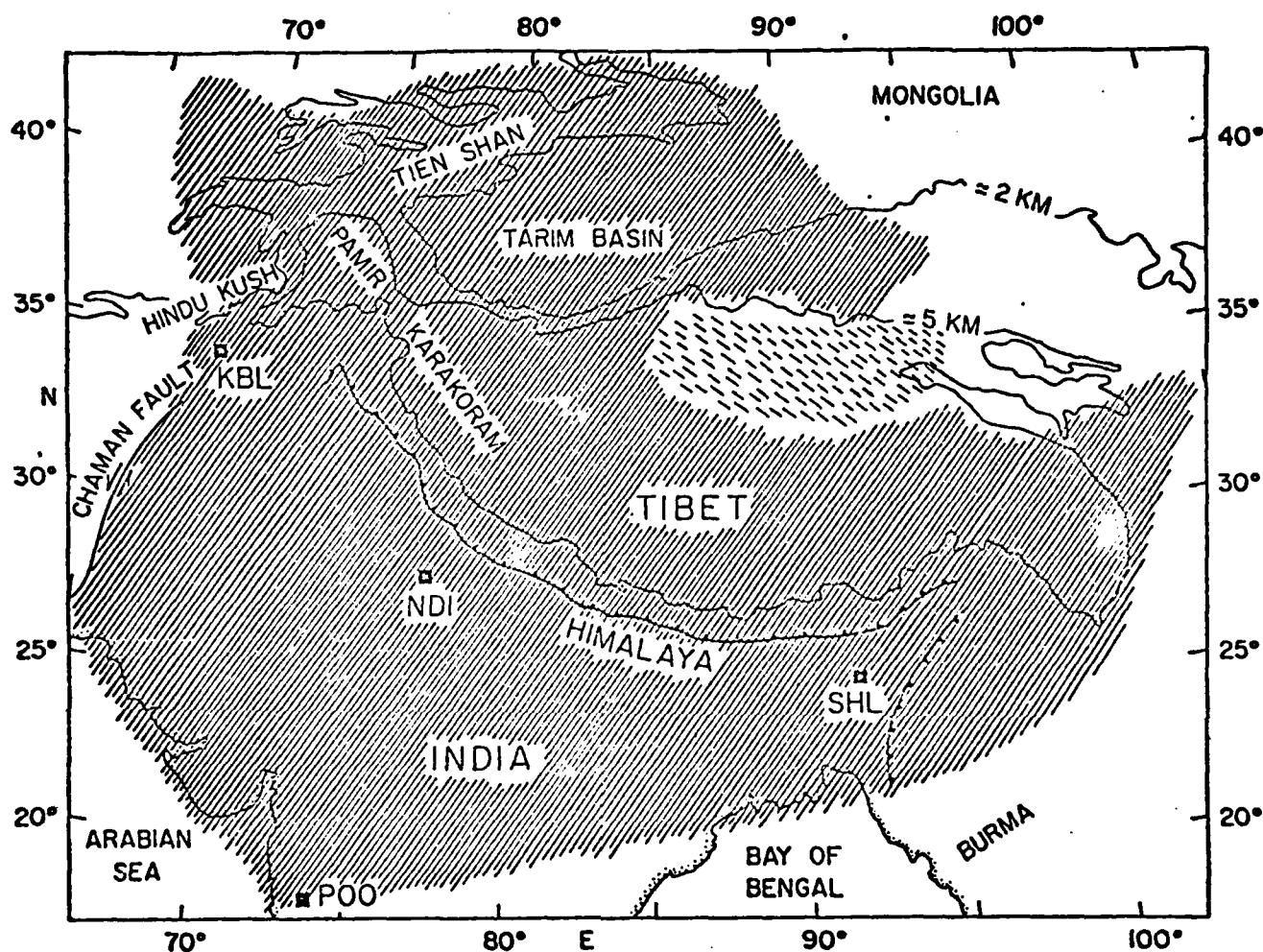
Figure 14: Map of Tibet and the surrounding regions showing zones of efficient (solid lines) and inefficient (dashed lines) S_n propagation. These patterns are determined using data produced by the WWSSN stations of KBL, NDI, SHL, and POO that are shown on the map. The zone of inefficient S_n propagation in northern Tibet is closely related to the Chang Thang terrane which exhibits numerous subrecent volcanics. The efficient S_n propagation beneath most of Tibet suggests that the uppermost mantle material is not anomalous (i.e., high Q) and is probably similar to that which exists beneath shield and stable continental regions.
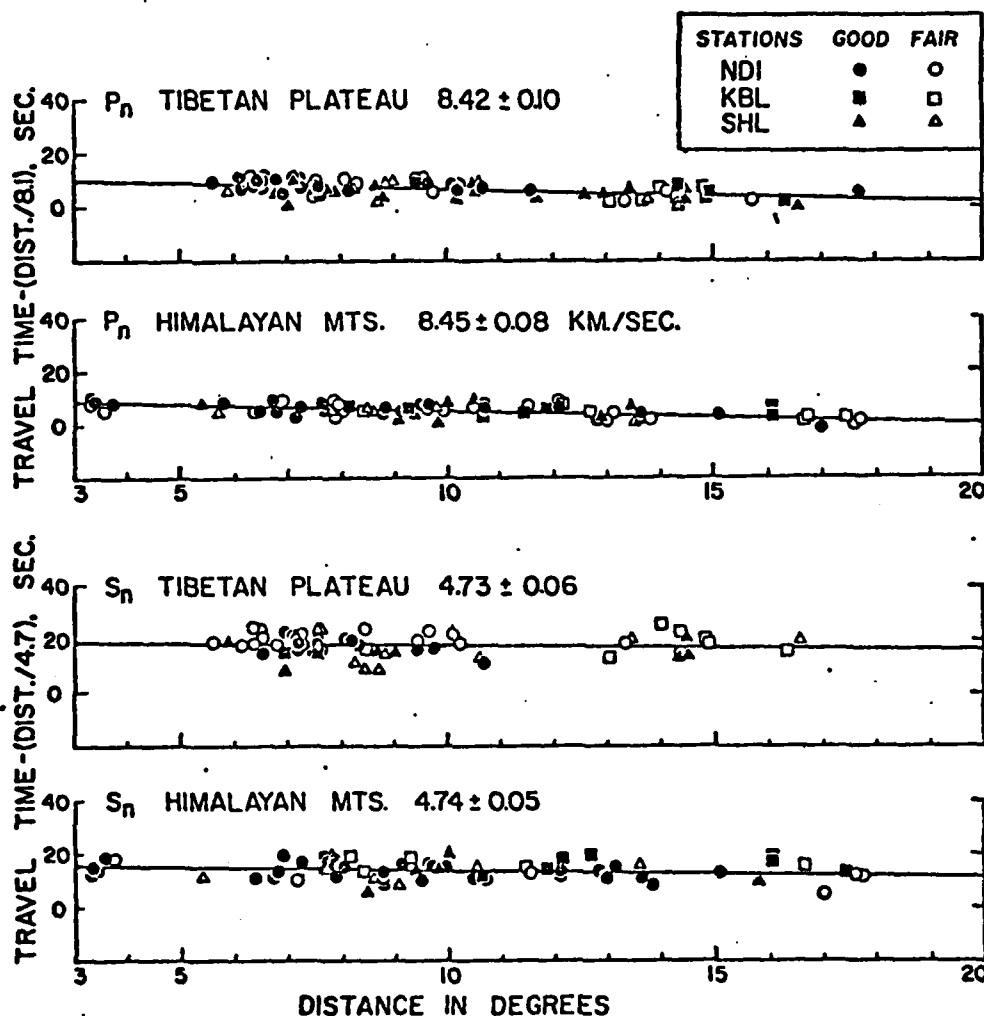
Figure 15: Travel-time plots of Pn and Sn data for propagation paths that are mostly either contained in the Tibetan plateau or in the Himalayan mountains, including data from KBL, NDI, and SHL WWSSN stations (see Figure 3). Solid symbols indicate impulsive arrivals for Pn and clear arrivals for Sn. Open symbols indicate emergent, but clear, arrivals for Pn and fair arrivals for Sn. The calculated velocities from the data are shown.
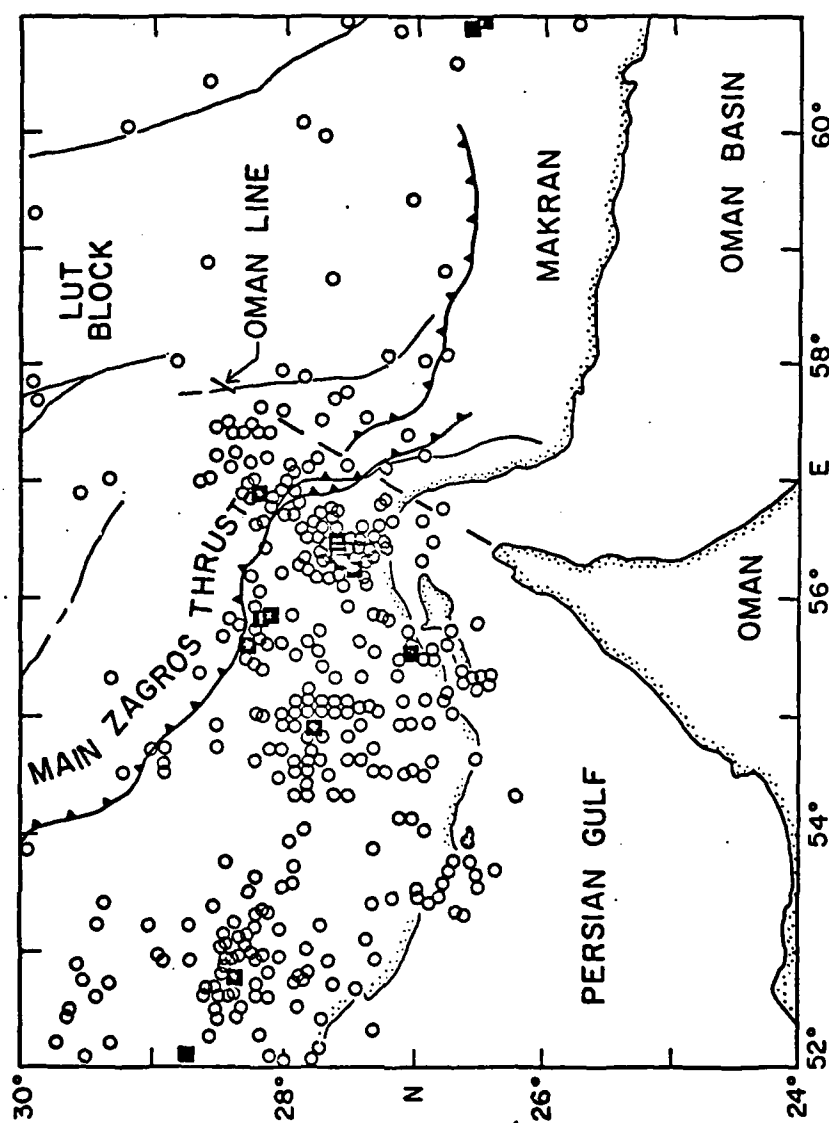
Figure 16: Seismicity map of southern Iran (from PDE; 1961-1978) showing the transition zone (i.e., the Oman Line) between the continental collision zone of Zagros (along the Main Zagros Thrust) and the inferred oceanic subduction zone beneath the Makran region. The solid squares represent events with determined focal mechanisms. We are investigating the nature of this transition zone and the depth of earthquakes in this area.

RELATIVE AMPLITUDES AND DELAY TIMES OF
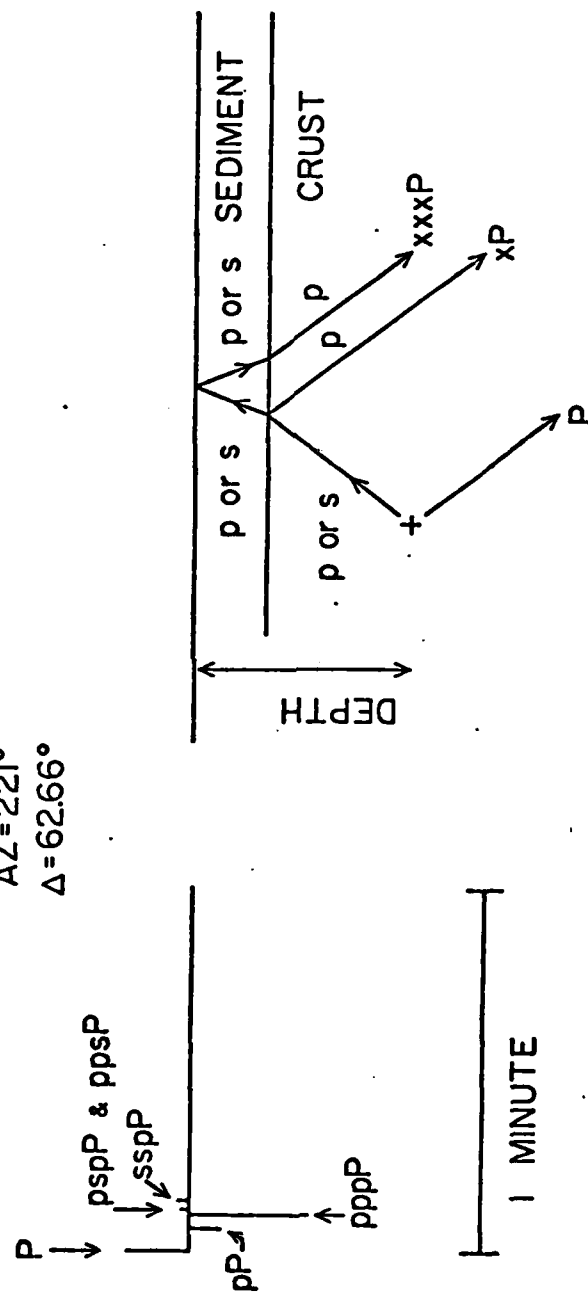STRONGEST PHASES RECORDED AT WIN

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Figure 17: Diagram (on the right) showing the different possible seismic phases, including the direct P and reflected P and S waves, that are used to obtain synthetic P waveforms. The stick diagram on the left shows the relative amplitudes and delay times of strongest phases recorded at the WWSSN station WIN for the Khurgu main shock on March 21, 1977.
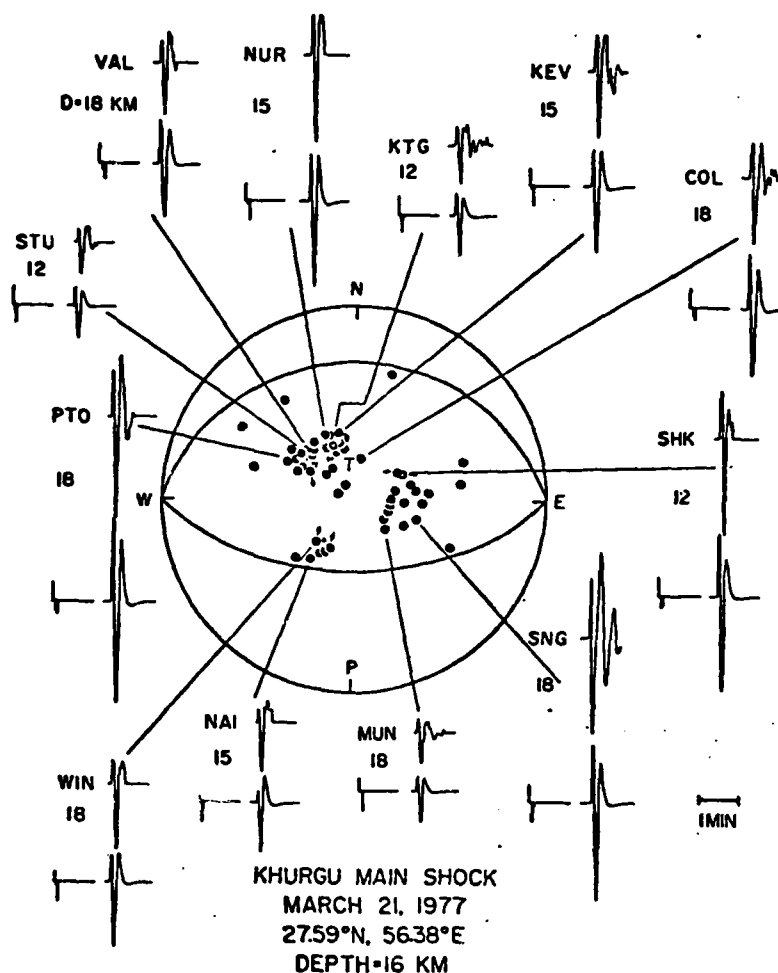
KHURGU MAIN SHOCK
MARCH 21, 1977
27.59°N, 56.38°E
DEPTH=16 KM

Figure 18: The preferred focal mechanism (equal area projection of the lower hemisphere) for the Khurgu main shock with the observed (top) and synthetic (bottom) seismograms for WWSSN stations for which the P signals are clear enough to be modelled. The positions of the stations on the focal sphere are affected by using a crustal velocity of 6.8 km/sec. Solid circles represent compressional first motions, and S wave polarizations are represented by arrows. For modelling the P waveforms we assumed a crustal structure at the source that includes a 5 km thick layer of sediments (Vp = 5.0 km/sec) overlying a crustal material for which Vp = 6.3 km/sec extending down to the depth of the source. All seismograms are normalized to the same height. The stick diagrams show the relative amplitudes and the arrival times of the strongest phases used in constructing the waveforms, including the direct P and the different reflected P and S waves. For any given station we show the depth of the source for which we obtain the best matching of P waveforms. An average depth of 16 km is obtained for this event.

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The Middle East study is focused on the Turkish and Iranian plateaus and the surrounding regions. Sn amplitude variations are very striking in these areas. Efficient Sn propagation is observed across a major part of the Turkish and Iranian plateaus. However, Sn is strongly attenuated in the northernmost part of the plateaus south of the Black and Caspian Seas, and in the area between these two seas. These regions are characterized, in general, by active tectonism, including volcanism, faulting, and folding. However, this active tectonism is

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not restricted to the areas of high Sn attenuation, but appears to extend, though with somewhat less apparent activity, beneath a major part of the Turkish and Iranian plateaus. Patterns of lateral variations in the propagation of Lg are not as consistent as those for Sn. Lg propagates efficiently across Turkey, Iran and adjacent regions, but the Lg waves that cross the Turkish and Iranian plateaus are, in general, weak and have relatively long predominant periods of about 2-5 seconds. The Lg phase is not observed when the path of propagation crosses the southern Caspian and the Black Seas, consistent with the available evidence of oceanic-type crustal structure beneath these seas.